SECTION 1. ADMINISTRATIVE INFORMATION

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SECTION 2. PUBLIC SUMMARY:

Forests in the Eastern United States are changing in response to ecological succession, tree harvest and other disturbances and climate change has the potential to further change these forests. We predicted the distribution and abundance of common tree species across portions of the Eastern U.S. under alternative climate scenarios that varied in the amount of warming by the end of the century from 1.1 to 4.2 degrees C. We used a forest landscape change model to forecast changes in tree abundances and distribution in the North Atlantic region of the U.S. while accounting for climate change, succession, and harvest. We then considered a broader region of the U.S. and combined our results with results from previous studies to compare forecasts from three different modeling approaches for the Central

Hardwood, Central Appalachian, Mid-Atlantic, and New England regions of the U.S. to determine the level of agreement among models. Our forecasts for the North Atlantic region indicated tree abundances were affected first by succession and harvest but second by climate. We predicted an Increase in Southern and Central Hardwood species and a decrease in Northern Hardwood and spruce-fir forest species under warming climates over the next 300 years. Our comparison of the three modeling approaches across the Eastern U.S. indicated high agreement for many species, especially northern species modeled to lose habitat in coming decades. There was agreement among models for decreases in black spruce, balsam fir, northern white cedar, and red spruce, and increases in loblolly pine and some oaks and hickories. Agreement across different modeling approaches and different climate scenarios provides strong evidence of potentially important changes to forests in response to climate change. These results can be used to guide decisions about how to manage forests under climate change to continue to provide the benefits we derive from them.

SECTION 3. PROJECT SUMMARY:

Forests in the Eastern United States are in the early- and mid-successional stages recovering from historical land use. Succession, harvest, and climate are potentially important factors affecting forest composition and structure in the region. Our goal was to predict the distribution and abundance of dominant tree species across portions of the Eastern U.S. under alternative climate scenarios from present to the end of the century. We used the forest landscape change LANDIS PRO and hybrid empirical-physiological ecosystem model LINKAGES to model changes in forest biomass and species abundances and distribution in the North Atlantic region of the U.S. while accounting for climate change, succession, and harvest. We considered three climate scenarios defined by a general circulation model and emission scenario: PCM B1, CGCM A2, and GFDL A1FI. We then compared results from three alternative modeling approaches; LANDIS PRO, LINKAGES, and TreeAtlas for the Central Hardwood, Central Appalachian, Mid-Atlantic, and New England regions to determine agreement among models and establish a stronger inference for projected changes through model averaging. Tree Atlas is a statistically derived enhanced niche model in contrast to the process driven ecosystem and landscape models LINKAGES and LANDIS PRO.

Model simulations for the North Atlantic region indicated future above ground biomass averaged 10% greater under the CGCM A2 and GFDL A1FI scenarios than under the PCM B1 scenario and current climate. Climate change effects on tree species abundance and distribution were not evident from 2000 to 2100. However by 2300, occurrence of northern hardwood maple/beech/birch forest species and spruce/fir forest species decreased in occurrence and central hardwood and southern tree species increased in occurrence and shifted northward. The future dynamics of forest biomass and species abundances were primarily attributed to succession but warmer climates had positive effects on forest biomass. Southern species and central hardwood tree species increased at the expense of the Northern Hardwood and Spruce-Fir forest species under warming climates and at some point beyond the 300 year time frame examined here some species may be extirpated from the region.

Our comparison of LANDIS PRO, LINKAGES, and TreeAtlas for the Central Hardwood, Central Appalachian, Mid-Atlantic, and New England regions indicated high agreement for many species, especially northern species which lose habitat in coming decades. TreeAtlas and LINKAGES outputs of suitable future habitat were most in agreement, but each had reasonable agreement with many species outputs from LANDIS, particularly when LANDIS was simulated to 2300. We found this unified analysis of multiple models to be a useful approach that can provide a more unified results for use by stakeholders.

We recommend the continued use of multiple modeling approaches and multi model inference to reduce uncertainty associated with particular modeling frameworks. Climate change remains another critical uncertainty that we think should continue to be addressed by examination of multiple climate scenarios and incorporation of the uncertainty in decision making processes. Lastly, we suggest continued efforts to assess uncertainties in the two process based models used here through sensitivity analyses and critical assessment of key parameter values.

SECTION 4. REPORT BODY:

Purpose and Objectives:

Our goal was to predict the distribution and abundance of dominant tree species across the Northeastern U.S. under alternative climate scenarios from present to the end of the century. Specific objectives were 1) to complete forest landscape modeling for the New England region under alternative climate scenarios and 2) to synthesize results with comparable ongoing efforts in the eastern U.S. to provide a comprehensive and spatially explicit assessment of potential change in forest composition, structure, and distribution. We met both these objectives with some modification to objective 2 from the original proposal. We originally proposed to include landscape modeling efforts from the Great Lake States but the original principal investigators decided these efforts were either not suitable for comparison or were not complete enough by the conclusion of this project to include in the synthesis and comparison. Therefore the synthesis and comparison was based on the New England, Mid-Atlantic, Central Appalachian, and Central Hardwood Regions, and did not include the Great Lake States.

Organization and Approach

Objective 1

Study area

Our study area included forests in the Northeastern United States and covered 42,175,660 hectares from northern Pennsylvania and New Jersey northward to Maine (Fig. 1.1). The area included 20 ecological sections and 82 subsections that represented a diversity of vegetation, geography, and climate (Cleland et al. 2007). Most of the area was in the Appalachian Highlands physiographic division including the Piedmont and Appalachian Mountains and was highly forested rolling hills to summits greater than 1500m. The Atlantic coastal plains along the east coast ranged from flat to moderately dissected irregular plains. The area had highly variable climates that were affected by the Atlantic Ocean in coastal areas, Great Lakes in the inland regions, and Appalachian Mountains in the southern region. This area also had a strong seasonal cycle with warm and humid summers and cold winters punctuated by heavy snow and ice. Average mean temperature ranged from 3 to 10°C and mean precipitation ranged from 79 to 255cm (McNab et al. 2007).

Approach

We used the LANDIS PRO Succession module to simulate tree growth, aging, fecundity, dispersal, resprouting, establishment, and competition (Wang et al. 2013, 2014a). We modeled the 24 most abundant tree species based on basal area in the FIA data (Table 1.1). The initial forest conditions included number of trees, by age cohort for 24 tree species at year 2000 and were directly derived from diameter at breast height (DBH) for each species using 1995-2005 FIA plot data including trees $\geq$ 2.54 cm (Dijak 2013; Wang et al. 2014b). We derived the biological traits for each species including species longevity, maturity, shade tolerance, dispersal distance, sprouting probability, maximum stand density index, and maximum DBH from previous studies and literature (Appendix Table 1, Burns and Honkala 1990, Wang et al. 2013, 2014b, 2015).

We used LANDIS PRO Harvest module to simulate clearcutting in the conifer forests (mainly in Maine) and partial harvest in the northern hardwood forests (Fraser et al. 2013). We incorporated varying harvest regimes for each FIA unit to capture the variations in harvest regimes across the region (Canham et al. 2013). We derived minimum stand entering basal area, residual stand basal area, proportion of forest land harvested/decade, and tree species harvest preferences for each harvest regime from FIA data based on the 1995-2005 harvest records.

We captured the abiotic controls in soil, terrain, climate, and vegetation by stratifying the whole northeastern region into 656 landtypes by intersecting 82 ecological subsections and 8 landforms derived from a digital elevation model (Dijak 2013). We incorporated the regional climates by intersecting subsections with downscaled general circulation model predictions. We obtained the soil parameters including organic matter, nitrogen, wilting point, field moisture capacity, percent clay, sand and rock for each landtype from Natural Resources Conservation Service soil survey (Soil Survey Staff, http://soils.usda.gov/). We assumed resource availability (measured as maximum growing space, MGSO) and species colonization (measured as species establishment probability, SEP) were uniform within a landtype and different among landtypes. Climate change affected tree mortality through modifying MGSO and species colonization through modifying SEP at each modeled time step(Wang et al. 2014). We modeled MGSO and SEP under current and future climate conditions using LINKAGES II ecosystem model that simulated individual tree species growth, regeneration, and mortality accounting for nitrogen availability, temperature, precipitation, wind, solar radiation and soil moisture (Wullschleger et al. 2003; Wang et al. 2014a).

We considered a current climate scenario and three future climate change scenarios that consisted of a general circulation model paired with an emission scenario: PCM B1, CGCM A2, and GFDL A1FI. The PCM, CGCM, and GFDL models predicted the lowest, moderate, and highest increases in temperature and B1, A2, and A1FI predicted the least, moderate, and most fossil fuel intensive emission scenarios in the region, respectively (IPCC 2007). Thus, by simulating these climate scenarios, we were able to incorporate uncertainty in future climate change projections for the region (IPCC 2007). For the current climate scenario, we obtained the daily climate data for a 30-year period (1980-2009) including the daily maximum and minimum temperature, daily precipitation, daily solar radiation, and day length at 1 km resolution for 1980-2009 from DAYMET (Thornton et al. 2012) for each ecological subsection., We obtained down-scaled climate change data for three climate change scenarios for the period 2070-2099 for each ecological subsection from the U. S. Geological Survey Center for Integrated Data Analysis Geo Data Portal (Stoner et al. 2011). We then conducted LINKAGES II simulations using above climate and soil data. LINKAGES simulations were replicated 30 times and mean biomasses evaluated. The maximum simulated biomass for each species during the first 30 years modeled under current climate for years 1980-2009 and three climate change scenarios for years 2070-2099 were used to estimate SEP for each landtype at year 2000 and year 2100 respectively (He et al. 1999). MGSO was estimated from relative biomass levels from LINKAGES simulations using endemic species groups for each subsection at simulation year 100(Wang et al. 2015; Wang et al. in press).

We conducted LANDIS PRO simulations for the current, PCM B1, CGCM A2, and GFDL A1FI climate scenarios and simulated the same harvest regimes under the four climate scenarios. We predicted forest changes from year 2000 to 2300 using 10-year time step at 270 m spatial resolution with five replicates for each climate scenario to capture the stochastic variations. For three climate change scenarios, we linearlyinterpolated the changes in SEP and MGSO from 2000 to 2100 in decadal increments and held the values constant from 2100 to 2300. Thus, our predictions represented linear decadal changes in climate for the first 100 simulation years but no change for the subsequent 200 simulation years.

Analysis

We analyzed the differences in total AGB and tree species distribution for the whole region among scenarios at year 2050, 2100, and 2300 to represent the short-, medium-, and long-term responses, respectively using LANDIS PRO. We summarized the total AGB under each climate scenario by averaging predictions from the five replicates and calculated the percent changes in total AGB under PCM B1, CGCM A2, and GFDL A1FI climate scenarios compared to current climate scenario at year 2050, 2100, and 2300 for the whole region and each ecological section. We calculated species occurrence as percentage of total forested cells in which a given species was present. We tested the hypotheses that climate scenario, year, and the interaction between year an climate had no effect on total AGB and percent occurrences for 24 tree species using a repeated measures Analysis of Variance in which the data consisted the total AGB and species occurrences at year 2050, 2100, and 2300, and year was treated as a repeated factor. We refer to the year effect as succession because it represents change over time due to species, stand, and landscape processes.

We summarized species distribution changes as expansion or contraction if a species occurrence increased or decreased, respectively, from 2000 to 2050, 2100, and 2300. To further examine the spatial changes in species distributions we calculated (1) extinction rate - the percentage of raster cells of the current climate scenario where a given species was absent under climate change scenarios, (2) colonization rate - the percentage of raster cells where a given species was absent under current scenario but colonized, and (3) persistence rate – the percentage of raster cells of the current climate scenario where a given species was also present under climate change scenarios at year 2050, 2100, and 2300.

Objective 2:

Study area

The study areas consist of much of the forested land in the central and northern portions of the eastern United States (Fig. 2.1). The area was modeled in four regions: the Central Hardwoods (CH), Central Appalachians (CA), Mid-Atlantic (MA), and New England (NE). Among these regions, sizable differences in attributes are apparent (Table 2.1). Mean annual temperatures range from 13.0°C in CH to 6.4°C in NE now, with future projections of 14.2° to 7.6°C under PCM (mild) and 17.5° to 10.3°C under GFDL (harsh) scenarios (Table 2.1). Estimates of precipitation did not vary widely across regions or scenarios, although CH is modeled to have higher annual precipitation under PCM and lower annual precipitation under GFDL, while the other regions had estimates of level or slightly higher annual precipitation. However, with the warmer conditions, and with currently realized and projected future larger daily precipitation events followed by longer drought periods "hot droughts" can be expected to increase forest mortality (Allen et al. 2015). Elevations are substantially higher in the CA and lower in the CH. Organic content increases SW to NE, while percent clay does the opposite; these two together account for the variation in nutrient levels and water holding capacity which effect individual species responses.

Each of the regions has been the focus of a vulnerability assessment and coordinated by the Northern Institute of Applied Climate Science (NIACS) and detailed reports have been published for the Central Hardwoods (Brandt et al. 2014) and Central Appalachians (Butler et al. 2015), with pending publications on the other two regions (Janowiak et al. in prep, Butler et al. in prep).

Approach

The TreeAtlas, LINKAGES, and LANDIS PRO models were applied to each region as part of previously mentioned vulnerability assessments and for this project. We compared predictions across these three fundamentally different models.

TreeAtlas uses a RandomForest (Prasad et al. 2006) statistical approach to model current and potential future suitable habitat with forest inventory and environmental variables enhanced with Modification Factors on each of 134 tree species (Iverson et al. 2008b, Iverson et al. 2011, Matthews et al. 2011). The outputs are presented in a web-based Climate Change Tree Atlas which incorporates a diverse set of information about potential shifts in the distribution and abundance of tree species' habitat in the eastern United States over the next century (LandscapeChangeResearchGroup 2014). It also provides a reliability rating for each model based on statistically quantified measures of fitness (Iverson et al. 2008b). Importantly, TreeAtlas projects where the habitat suitability may potentially change for a particular species, but does not project where the species may actually occur by a certain time. The actual rate of migration into the new suitable habitat will be influenced by large time lags, dispersal and establishment limitations, and availability of refugia. The model uses inputs of tree abundance, climate, and the environment to simulate species' habitats. Tree abundance was estimated from the U.S. Forest Service's Forest Inventory and Analysis (FIA) data plots (Miles et al. 2006)

LINKAGES as decribed under objective 1 is a forest ecosystem process model and like TreeAtlas, this application of LINKAGES provides a prediction of the change in future habitat suitability for individual tree species and is not a simulation of actual forest change. We aggregated the predicted biomass estimates from these studies from landforms to subsections and subsections to sections using area-weighted means and calculated change ratios as the quotient of future biomass divided by current biomass for each species in a section.

LANDIS PRO, as previously described and hereafter referred to LANDIS, is a forest landscape model that projects changes in forest composition and structure due to species-, stand-, and landscape-level processes (Wang et al. 2013, 2014a). Wang et al. (2015; In Review) used LANDIS to simulate changes in forest composition and structure due to succession, windthrow, harvest and climate change for the climate scenarios and study area used in this study. LANDIS does not directly consider climate, however, effects of climate change were incorporated by varying (SEP), which affect species colonization, and the (MGSO), which affects tree mortality, as a function of climate, soil, and terrain. MGSO and SEP were modeled under current climate and each future climate using LINKAGES and then changed linearly from current climate to the end of the century under each climate scenario. We calculated species importance values for each cell at the start of simulations and at year 2100 (hereafter Landis100) and 2300 (hereafter Landis300) under each scenario and the ratio of future to current levels of importance values. However, because the climate scenarios only forecasted climate change up to 2100, SEP and MGSO were held constant for simulations from 2100-2300 and did not consider climate change beyond 2100 but did account for an additional 200 years of stand dynamics in response to the climate change that occurred up to 2100. Unlike TreeAtlas and LINKAGES, Landis simulated stand dynamics, colonization, and extinction and represented projections of actual change in forest composition and structure.

We calculated a change ratio as the quotient of a species future importance (Tree Atlas and Landis) or biomass (Linkages) and current importance or biomass. Future values were based on 2100 (100 years) for Tree Atlas and Linkages and 2100 annd 2300 (100 and 300 years) for Landis. If the change ratio is one, no change is projected; if >1, an increase is projected; if < 1, a decrease is projected. We created the following change classes based on change ratios to facilitate interpretation of some results: large increase (>2), small increase (1.2-2.0), no change (0.8-1.2), small increase (0.5-0.8), large increase (<0.5). New habitat was also observed in TreeAtlas for two species. We averaged change ratios across different combinations of models and regions to assess overall species vulnerability according to the mild and harsh scenarios, and both together.

We tallied agreement between the following pairs of models based on change ratios: 1) TreeAtlas & Linkages, 2) TreeAtlas & Landis100, 3) TreeAtlas & Landis300, 4) Linkages & Landis100, 5) TreeAtlas & Landis300, and 6) Landis100 & Landis300. We used an ordinal scale of 0–4 and assigned 4 points if both change classes were identical; 3 points if one class apart (e.g., No Change and Small Increase or Small Decrease); 2 points if two classes apart but still trending in same direction (e.g, No Change and Large

Increase or Large Decrease); 1 point if Small Decrease & Small Increase (opposite trend); and 0 points if opposite trend and one or both are Large Decrease or Large Increase.

We also calculated Spearman's rank correlations among combinations of models and scenarios as another measurement of agreement. We report correlations and p-values for the hypothesis that change ratios from a pair of models were not positively correlated and used Holm's method to adjust P-values to account for familywise error rate with multiple comparisons (Holm 1979), which is a fairly restrictive adjustment.

Lastly, after assessing agreement between models we calculated model averaged change ratios as the mean change ratio for each species from Tree Atlas, Linkages, and Landis for PCM, GFDL, and PCM and GFDL values combined. The means represents a single estimate of change derived from all three models and the range can be interpreted as a measure of uncertainty among models or scenarios.

Project Results, Analysis and Findings

Objective 1

AGB changes

Total AGB dynamics predicted by Landis for the North Atlantic region followed a similar pattern for the four climate scenarios. Total AGB increased rapidly from 2000 to 2120 followed by slight decrease until 2180, and then gradual increase to 2300 (Fig.1.2). The period of increase from 2000 to 2120 resulted from continued tree growth and self-thinning in these early to mid-successional forests recovering from historical land use in the area. The slight decrease that followed was because many short-lived tree species such as red maple and black oak that established in the early to mid-1900s reached maximum longevity and died and were replaced by young trees. The growth of newly established young trees then offset the longevity-caused mortality of long-lived tree species (e.g., white oak, sugar maple, and American beech) and thus resulted in another round of increase in total AGB to 2300.

Total AGB was significantly affected by climate ($P <.0001$), year ($P <.0001$), and the interaction between climate and year ($P <.0001$), which explained 29%, 64%, and 4% of the variation in total AGB, respectively. The highest total AGB was under GFDL A1FI followed by CGCM A2, current, and PCM B1 climate scenarios (Fig. 1.2). Total AGB under GFDL A1FI and CGCM A2 was nearly identical and was 13.4 Mg /ha (7.2%), 17.8 Mg /ha (9.1%), and 22.3 Mg /ha (11%) greater than that under the current climate scenario at year 2050, 2100, and 2300, respectively (Fig. 1.2). Total AGB under PCM B1 and current climate were similar over time (Fig. 1.2).

The effects of climate change on total AGB varied spatially across the region. The greatest increases in total AGB under climate change scenarios were the most northern subsections in Maine (e.g., International Boundary Plateau, St. John Upland, Aroostook Hills, and Aroostook Lowlands subsections) and hilly and upland subsections in the middle Atlantic coastal plains (e.g., Atlantic Southern Loam Hills and Delmarva Upland subsections) (Fig. 1.3). The greatest decreases in total AGB under climate change scenarios were some east-coast subsections in Maine (e.g., Central Maine Embayment and Main Eastern

Interior subsections) and some high-elevation mountain subsections in Adirondack-New England Mixed-Conifer Forests (e.g., White Mountains, Taconic Mountains, and Southern Piedmont Subsections), and some upland subsections in Northern Atlantic Coastal Plain (e.g., Western Chesapeake Uplands Subsection) (Fig. 1.3). The responses of tree species distribution to climate change varied spatially and temporally across the region.

Tree species distribution

The region-wide occurrences for 24 tree species were significantly affected by climate, year (succession), and the interaction between climate and year (succession) (Table 1.1). Climate and year explained 1~30%, 40~95% of variation in species occurrences, respectively (Table 1.1). The climate change effects increased over time with 5~40% variation in occurrences explained by the interaction between climate and year (Fig. 1.4). Climate change did not have much effect on the occurrences of the 24 tree species from 2000 to 2100 but had substantial effects on many by 2300 as evident by differences in percent occurrence among climate scenarios (Fig. 1.4). Extinction rates averaged 5 – 10% at 2050 and increased to 10 – 20% at 2100, whereas colonization rates averaged 5 – 15% at 2050 and increased to 10 – 25% at 2100 (Fig. 1.1, Fig. 1.2).

Changes in species distribution at 2300 generally fell into three groups based on the responses of species occurrence to climate change. The first group significantly contracted their distributions under the three climate change scenarios and included mostly cool-climate coniferous species and northern hardwood species (eastern hemlock, balsam fir, black spruce, red spruce, northern white cedar, eastern white pine, pitch pine, Virginia pine, quaking aspen, and yellow birch) and some central hardwood species (scarlet oak, black oak, and pignut hickory) (Fig. 1.4). Extinction rates averaged 40 – 90% at 2300, mostly occurring in the southern boundaries of their distributions (Fig. 1.5). The second group significantly expanded their distributions under three climate change scenarios and included mostly southern species (yellow-poplar and loblolly pine) and some central hardwood species (white oak and chestnut oak) (Fig. 1.4). Colonization rates averaged 30 – 60% at 2300, mostly occurring in the northern boundary of species distribution (Fig. 1.5). The third group had similar levels of extinction and colonization across the region under the four climate scenarios and included some northern hardwood species (American beech, sugar maple, black cherry, white ash, northern red oak, and red maple) and central hardwood species (shagbark hickory) (Fig. 1.4). Extinction rates and colonization rates averaged 20 – 35% at 2300 (Fig. 1.5).

We showed that total AGB dynamics followed similar patterns under four climate scenarios, suggesting that succession was an important driver of AGB dynamics. Succession in our model was the result of tree growth, aging, dispersal, seedling establishment, and competition. Given the importance of succession in total AGB dynamics, we believe it is important to use models that incorporate these successional processes when predicting future forest biomass at regional scales. The predicted total AGB under current climate scenario reached 240 Mg/ha, which is similar but slightly lower than the suggested value of 250~280 Mg/ ha from old-growth forest studies in the northeastern region because we included harvest in our simulations (e.g., Bormann and Likens 1979; Keeton et al. 2011; McGarvey et al. 2015); therefore, we concluded our model was performing acceptably.

Total AGB increased over the 21st century irrespective of climate scenario. This finding reasonably reflected the fact that the Northeastern forests were at early- to mid-successional stages and were far from the maximum stock capacity observed from old-growth studies (Luyssaert et al., 2008; Pan et al., 2011; Lichstein et al. 2009). The first period of increase in total AGB peaked at 2120 (approximately 160~200 years of age) were consistent with some empirical studies. For example, AGB increased and peaked at approximately 170 years of age (Bormann and Liken 1979); Forest biomass predicted by Ecosystem Demography (ED) continued the increase at least until the end of the 21st century (Albani et al. 2006); AGB from 2010 to 2060 predicted by LANDIS II forest landscape model accumulated at least until 2060 for the state of Massachusetts, U.S. (Thompson et al. 2011).

There is some uncertainty about biomass dynamics for the latter stages of forest succession (e.g., >200 years). Bormann and Liken (1979) predicted that AGB declined in stands 200-350 years of age and remained stable in stands > 350 years of age and their biomass curve has been used for regional carbon predictions (e.g., Smith et al. 2006). However, Keenton et al. (2011) found biomass only slightly declined as dominant trees exceeded 300 years of age and continued increasing to 400 years and more. In our predictions, AGB declined and reached nadir at 2180 (220-260 years of age), which was somewhat earlier than predicted by Bormann and Liken (1979) and Keenton et al. (2011). This was because forest harvest shortened the forest turnover rates through affecting the regeneration dynamics and post-harvest stand development. The second increase to 2300 (340-380 years of age) in our predictions was consistent with predictions of increasing biomass to age 400 and more (Ziegler 2000; Keenton et al. 2011) but not consistent with predictions of stable biomass at ages > 350 (Bormann and Liken 1979) or declining biomass after age 230-260 (Tyrrell and Crow 1994). These differences may arise from differences between our regional averaged results and site-specific results that may vary among sites. Although there were a range of possible results in the latter stages of forest succession, we can make generations that, AGB will first increase and then decline as dominant short-lived tree species reach the longevity and eventually has potential to sequester into very late stage of succession (e.g., 400 years) in the Northeast Forests.

Climate change generally had positive effects on AGB in the Northeast mainly because of warmer temperatures and longer growing seasons (e.g., 10% increase under CGCM A2 and GFDL A1FI). Our regional averaged predictions were consistent with others that suggested climate change may play positive effects on future biomass in this region (Thompson et al. 2011; Campbell et al. 2009). However, there were great spatial variations in the effects of climate change on AGB across the region. Climate change increased the AGB for the cool-climate conifer forests in northern Maine and loblolly-shortleaf pine forests in uplands within the Middle Atlantic coastal Plains. This was because warmer and wetter climates, and longer growth season increased the productivity for cool-climate communities (e.g., spruce, fir, eastern hemlock, Virginia pine, and pitch pine), central hardwood species (e.g., white oak and shagbark hickory), northern hardwood species (e.g., chestnut oak, quaking aspen, and yellow birch), and southern species (e.g., yellow-poplar and loblolly pine). However, climate change decreased the AGB for the northeastern mixed forests in east-coast Maine, and northern hardwood forests in the Northern Atlantic Coastal Plain, and Adirondack-New England Mixed-Conifer Forests in the high-elevation mountain areas because climates in these areas were projected to become warmer and drier that would decrease the forest productivity. Furthermore, warmer temperatures drove the upward shift of the Northern Hardwood-Spruce-Fir forests to the top of these high-elevation mountains that resulted in greater amount of north hardwood species and lesser amount of carbon-dense, spruce-fir forests and thus decreased the total AGB. However, we did not consider the direct effects of rising atmospheric CO_2 and CO_2 fertilization on tree growth and indirect effects of climate change such as increase hurricane intensity and insect outbreaks, which may contribute to uncertainty in our predictions.

Climate change effects on tree species distribution were not evident until after 2100, reflecting the lagged responses of trees species to climate change through considering species demography. Our process or mechanistic simulation approach suggested that changes in tree species distributions in response to climate will take hundreds of years, which is longer than often inferred from niche based model predictions which suggest unsuitable habitat conditions for most of northern coniferous species by end of 21st century (e.g., Iverson et al. 2011; Morin and Thuiller 2009). In the long term, however, our predictions generally agreed with other studies suggested the northward shift and expansion of central hardwood tree species and southern tree species and northward shift and contraction of northern hardwood maple/beech/birch tree species and other cool-climate conifer species under climate change. This will have significant implications on the wildlife habitat, recreational value, and pulp and paper industry in the northeastern region, where the forest-based manufacturing industry is the central to the local economy (Shifley et al. 2012). Our findings also have important implications for management for mitigation and adaptation to climate change. For example, forest management that favors carbon-dense southern species and central hardwood species may promote the resilience and adaptation to climate change, and some species may not be able to rapidly expand in newly suitable climates without assisted migration.

Objective 2

We tabulated change classes for species by region, model, and climate scenarios and sorted species by TreeAtlas GFDL results (Table 2.2). Some general patterns in species changes were: 1) much less change under for all models under PCM than GFDL; 2) TreeAtlas and Linkages change classes were dominated by no change or small increases or decreases under PCM; 3) Landis100 had small changes under either PCM or GFDL but Landis300 showed more larger changes. TreeAtlas-Linkages had the highest agreement scores on our ordinal scale of 0–4 when averaged across species, with 3.4 for PCM and 3.16 for GFDL (Table 2.3). Next in agreement was Landis100-Landis300 (3.07-3.11), followed by Linkages-Landis100 and Linkages-Landis300 for PCM. TreeAtlas-Landis300 tended to agree highest with the GFDL scenario (2.78 vs. 2.48 on PCM), while Linkages-Landis300 agreed relatively more for the PCM scenario (2.92 vs 2.60 on GFDL). These relationships generally held across regions, although TreeAtlas-Landis300 (GFDL), for example, scored very high in agreement for CentApps, but even lower than PCM for NewEngland.

There was a wide range in agreement scores for the 36 species but some of the northernmost species (e.g., black spruce, balsam fir, northern white cedar, and red spruce) had maximum agreement among models (Table 2.4). These four species scored highest regardless of scenario or whether or not Landis100 (which tended to less modeled change) was included. On the other end of the agreement list were a few pines (shortleaf, loblolly, pitch, and Virginia), quaking aspen, post oak, tulip poplar, yellow birch, and American beech. Virginia and loblolly pine had low prominence in these regions which could contribute to less reliable models. Quaking aspen had models in NewEngland for large increases under Landis100/300 and large decreases in TreeAtlas and Linkages, while the reverse was true for shortleaf pine, and to a lesser extent, post oak, in CentHard. Many of the oaks, hickories, and maples fell in the middle to high side on agreement, for example most models show a decline in sugar maple especially in the more southerly regions of CentHard and CentApps (Tables 2.2, 2.4).

There were 83 species-region combination when we pooled species for the correlation analysis. The highest correlations between model-scenario pairings were between Landis100 PCM and Landis100 GFDL (r=0.98 or 0.99; Fig. 2.2; Table 2.5), which is not surprising because change was predominately driven by succession the first 100 years in Landis (Wang et al. 2015, In Review). Landis100 vs. Landis300 were also highly correlated regardless of scenario, but especially so within the same scenario. High correlations also occurred between the two scenarios for TreeAtlas or Linkages across most combinations of species and regions (Table 2.5). There were also highly significant correlations generally between TreeAtlas and Linkages outputs for both scenarios; only the CA region had no relationship between models apparent for its 15 species (also attributable to relatively low sample size) (Table 2.5).

Importantly, however, correlations increased between TreeAtlas and Landis when Landis simulations increased from 100 to 300 years. This was especially true over all species and regions for the Landis GFDL vs. either TreeAtlas scenario, where the correlation increased from 0.23-0.25 (NS) for 100 to 0.48-0.51 (P<0.0001) for 300 year Landis simulations; the same pattern is true for both Linkages and TreeAtlas throughout regions although not always significant (Table 2.5).

We averaged model predicted change ratios for each species across all four models, all four regions, and under PCM, GFDL, or both scenarios (Table 2.6). Seven northern conifers were predicted to fare the worst under climate change: black spruce, balsam fir, northern white cedar, red spruce, eastern hemlock, eastern white pine, and pitch pine. All seven northern conifers had an average change ratio <0.8 and the first four were large decreasers and more than half of their importance was lost and none of the models predicted increases (Table 2.6). Some species had a wide variation among models, including trends of opposite sign among models. Most striking is pitch pine, with Landis300 projecting a complete collapse in the NE and MA regions, while TreeAtlas and Linkages project small increases in NE. This discrepancy was likely because pitch pine succeeded to oaks in Landis simulations in the absence of fire. Tree Atlas and Linkages predicted declines in quaking aspen, but aspen increased in Landis simulations because it was less negatively affected by climate than northern conifers and took over growing space formally occupied by northern conifers. Sugar maple held its own under PCM but declined, especially in the more southern CA and CH regions, under GFDL. Many of the hardwoods and southern pines show overall average increases in future:current ratios across regions and models (Table 2.6). However, many of the averages are skewed by very high values, and that there is a wide variation including substantial losses in some regions under some models. We believe the greatest discrepancies among models occurred when stand or successional dynamics were important determinants of future species abundances because Landis was the only model to simulate these.

Conclusions and Recommendations

We showed that total AGB dynamics followed similar patterns under four climate scenarios, suggesting that succession was an important driver of AGB dynamics. Given the importance of succession in total AGB dynamics, we believe it is important to use models that incorporate these successional processes when predicting future forest biomass at regional scales. Climate change generally had positive effects on AGB in the Northeast mainly because of warmer temperatures and longer growing seasons. Our regional averaged predictions were consistent with others that suggested climate change may play positive effects on future biomass in this region. Future species abundances in the North Atlantic region were primarily affected by succession but under warmer climates southern species and central hardwood tree species increased at the expense of Northern Hardwood and Spruce-Fir forest species. At some point beyond the 300 year time frame examined here some species may be extirpated from the region.

Our comparison of LANDIS PRO, LINKAGES, and TreeAtlas for the Central Hardwood, Central Appalachian, Mid-Atlantic, and New England regions indicated high agreement for many species, especially northern species modeled to lose habitat in coming decades. TreeAtlas and LINKAGES outputs of suitable future habitat were most in agreement, but each had reasonable agreement with many species outputs from LANDIS PRO, particularly when LANDIS PRO was simulated to 2300. We found this comparison of multiple models to be a useful approach that can provide a more unified results for use by stakeholders.

We recommend the continued use of multiple modeling approaches and multi-model inference to reduce uncertainty associated with particular modeling frameworks. However, we think it is essential that at least one of the modeling approaches consider succession and harvest or other disturbances because of the importance of those factors, as demonstrated in this study. Climate change remains another critical uncertainty that we think should continue to be addressed by examination of multiple climate scenarios and incorporation of the uncertainty in decision making processes. We suggest continued efforts to assess uncertainties in the two process based models used here through sensitivity analyses and critical assessment of key parameter values. We plan on rerunning model simulations to incorporate a range of management options and updated climate scenarios for the region in the next year.

Outreach and Products

At the beginning of the project Frank Thompson met with Kevin McGarigal and corresponded with Scott Schwenk to ensure the project complemented ongoing efforts by the LCC. In addition the landscape simulated with the LANDIS model was based on GIS products produced by the LCC and results were summarized for the North Atlantic LCC region.

The results of this project are key components of the ongoing Mid Atlantic Climate Change Response Framework (http://www.nrs.fs.fed.us/niacs/climate/midatlantic/) and the New England Climate Change Response Framework (http://www.nrs.fs.fed.us/niacs/climate/newengland/). These projects are collaborative efforts involving federal, state, and tribal land management organizations, conservation organizations and private forest owners to factor climate change considerations into decision making and help implement adaptive responses to climate change. Frank Thompson, Louis Iverson, and William Dijak participated in expert panel vulnerability assessments and many of the contributors to this report will coauthor the vulnerability assessment reports.

Manuscripts

Wang, W. J., H. S. He, F. R. Thompson III, J.S. Fraser, B.B. Hanberry, and W.D. Dijak. 2015. The importance of succession, harvest, and climate change in determining future forest composition in a temperate hardwood forest. Ecosphere 6(12):277.

Wang, W. J., H. S. He, F. R. Thompson III, J.S. Fraser, and W.D. Dijak. In Review. Forest biomass and species distributions under climate change in the Northeastern U.S: accounting for effects of succession and harvest. Landscape Ecology (In review)

Iverson, L, F. R. Thompson, A. Prasad, S. Matthews, M. Peters, W. Dijak, J. Fraser, W. Wang, B. Hanberry, H. He, M. Janowiak, P. Butler, L. Brandt, C. Swanston. In Prep. Multi-model inference on the effects of climate change on forests in the Eastern U.S.: results from an enhanced niche model and process-based ecosystem and landscape models. Landscape Ecology (In Prep.)

Presentations:

Frank R. Thompson, Changes in Forest Composition and Structure Under Alternative Climate Scenarios in the Northeastern U.S., NECSC Spring Webinar Series, April 2015

Frank Thompson. Approaches to modeling landscape and climate effects on birds and forests in the Midwwestern U.S. Joint Sino-US Workshop on Forest, Soil, and Landscape Modeling, Changchun, China, June 21, 2015.

Hong He. The Role of landscape modeling in predicting regional forest change. Joint Sino-US Workshop on Forest, Soil, and Landscape Modeling, Changchun, China, June 21, 2015.

William D. Dijak, ; Brice B. Hanberry, Jacob Fraser, Hong S. He. Application of LINKAGES Version 3.0 to Determine Tree Growth Potential in Response to Global Climate Change. IALE World Congress, Portland, OR, July 2015.

Wen J. Wang, Hong S. He, Frank R. Thompson III, Jacob S. Fraser. Population dynamics can be more important than climate change for determining future tree species distribution change in a temperate deciduous forest. IALE World Congress, Portland, OR, July 2015

Frank Thompson, William Dijak, Hong S. He, Jacob S. Fraser, Wen J. Wang, Brice Hanberry. Application of the LINKAGES and landis models to project forest changes in the mid-atlantic region. Expert panel meeting for the Mid-Atlanitc Climate Vulnerability Assessement. Meeting hosted by the US Forest service Northern Institute for Climate Change Nov 17-19 2015, Philadelphia, PA

William Dijak, Frank Thompson, Hong S. He, Jacob S. Fraser, Wen J. Wang, Brice Hanberry. Application of the LINKAGES and landis models to project forest changes in the mid-atlantic region. Expert panel meeting for the New England Climate Vulnerability Assessement. Meeting hosted by the US Forest service Northern Institute for Climate Change Dec 2-3 2015, Burlington, VT

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Table 1.1. Results from a repeated measures Analysis of Variance to assess the effects of climate change, year, and the interaction between climate and year on the tree species distribution in terms of presence for 24 tree species in the northeastern United States

	Climate		Year		Climate*Year	
	Variation explained (%)	*P*	Variation explained (%)	*P*	Variation explained (%)	*P*
Eastern hemlock	3.33	<0.0001	88.88	<0.0001	7.60	<0.0001
Balsam fir	13.92	<0.0001	61.05	<0.0001	24.97	<0.0001
Black spruce	18.50	<0.0001	43.97	<0.0001	37.48	<0.0001
Red spruce	12.90	<0.0001	59.93	<0.0001	27.08	<0.0001
Northern white cedar	10.75	<0.0001	63.01	<0.0001	26.12	<0.0001
Eastern white pine	3.27	<0.0001	84.96	<0.0001	11.21	<0.0001
Pitch pine	4.30	<0.0001	84.01	<0.0001	11.55	<0.0001
Virginia pine	16.86	<0.0001	55.37	<0.0001	27.71	<0.0001
Quaking aspen	19.94	<0.0001	36.98	<0.0001	42.92	<0.0001
Yellow birch	11.18	<0.0001	62.67	<0.0001	25.21	<0.0001
Scarlet oak	12.62	<0.0001	58.34	<0.0001	28.76	<0.0001
Black oak	3.32	<0.0001	79.93	<0.0001	15.97	<0.0001
Pignut hickory	2.18	<0.0001	84.30	<0.0001	12.92	<0.0001
Yellow-poplar	30.46	<0.0001	44.98	<0.0001	24.30	<0.0001
Loblolly pine	28.38	<0.0001	44.97	<0.0001	25.76	<0.0001
White oak	24.17	<0.0001	47.78	<0.0001	26.98	<0.0001
Chestnut oak	21.17	<0.0001	57.68	<0.0001	20.26	<0.0001
American beech	1.35	<0.0001	97.31	<0.0001	0.92	<0.0001
Sugar maple	1.46	<0.0001	97.03	<0.0001	1.05	<0.0001
Black cherry	0.11	0.5066	95.04	<0.0001	3.75	<0.0001
White ash	6.00	<0.0001	85.58	<0.0001	3.28	0.0451
Northern red oak	4.79	<0.0001	89.58	<0.0001	3.94	<0.0001
Shagbark hickory	3.26	<0.0001	89.70	<0.0001	6.01	<0.0001
Red maple	0.32	0.0362	98.72	<0.0001	0.18	0.4826

Fig. 1.1. The Study area was located in the Northeastern United States spanning from northern Pennsylvania and New Jersey northward to Maine and covered 20 ecological sections and 42,175,660 hectares.

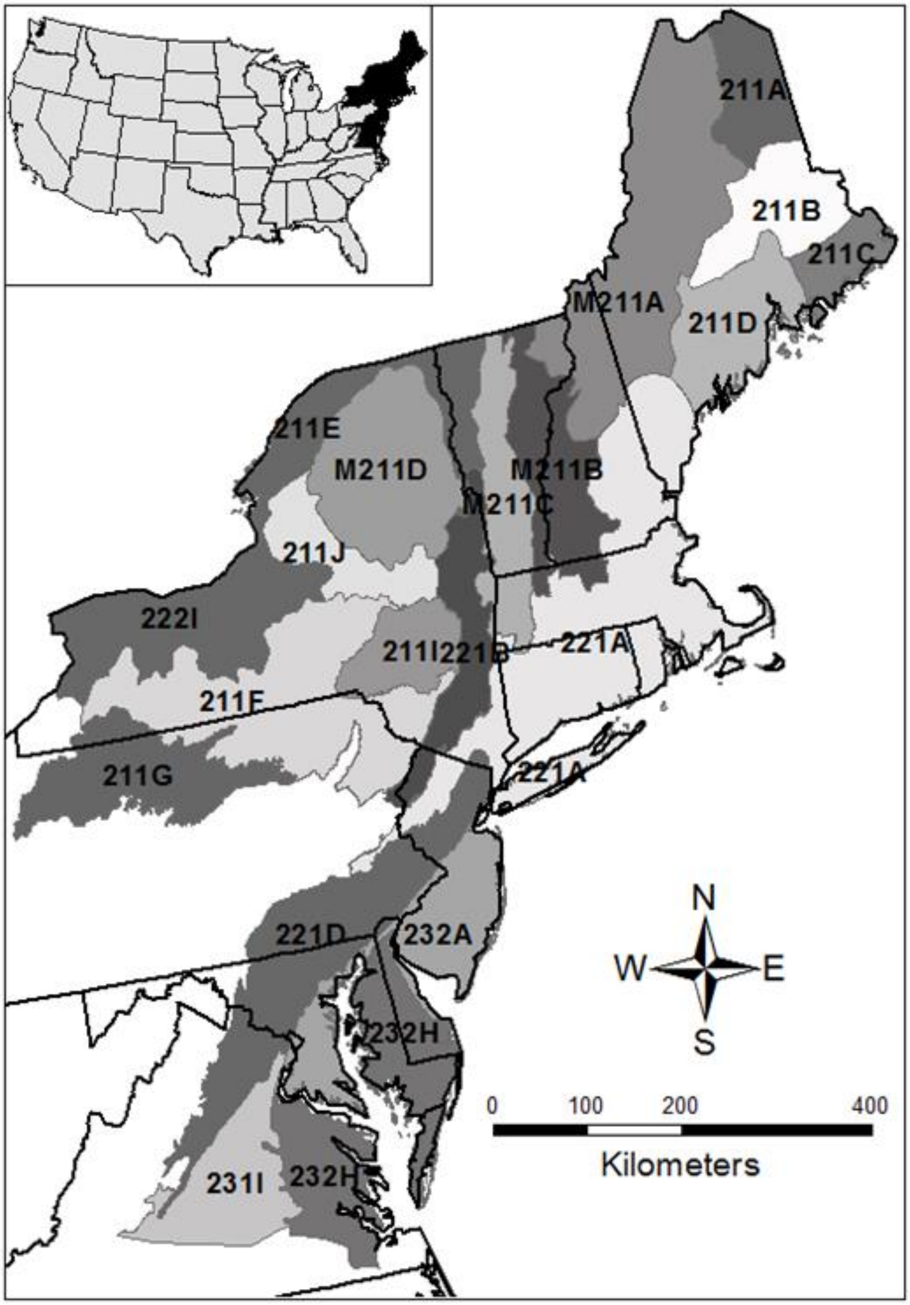

Fig. 1.2. Predicted total aboveground biomass (AGB, Mg/ha) under four climate modeling scenarios from 2000 to 2300 in the northeastern United States

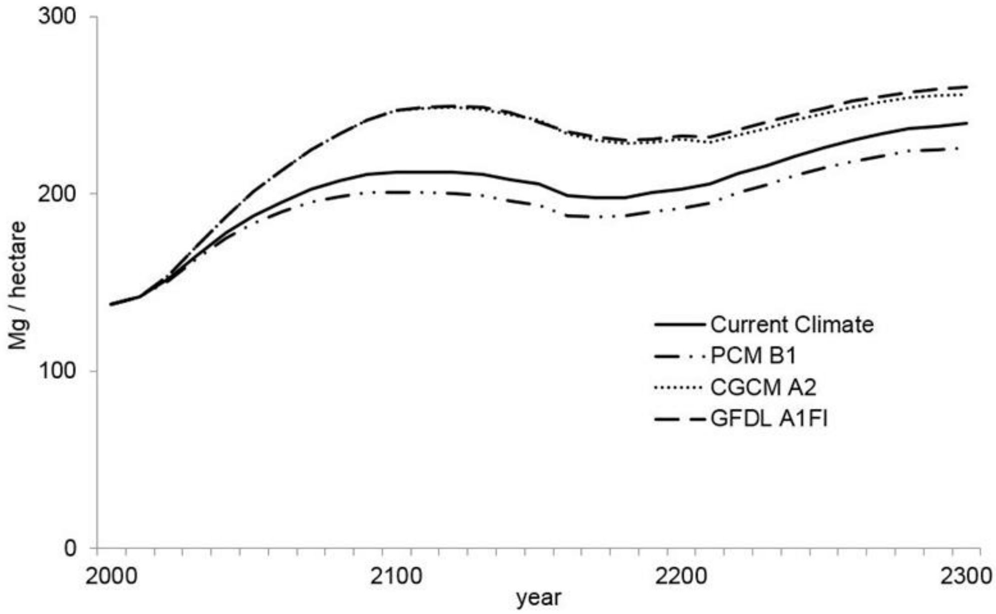

Fig. 1.3. The percentage changes in total aboveground biomass (AGB) between the climate change modeling scenario and current climate modeling scenario for each ecological subsection at year 2050, 2100, and 2300 in the northeastern United States.

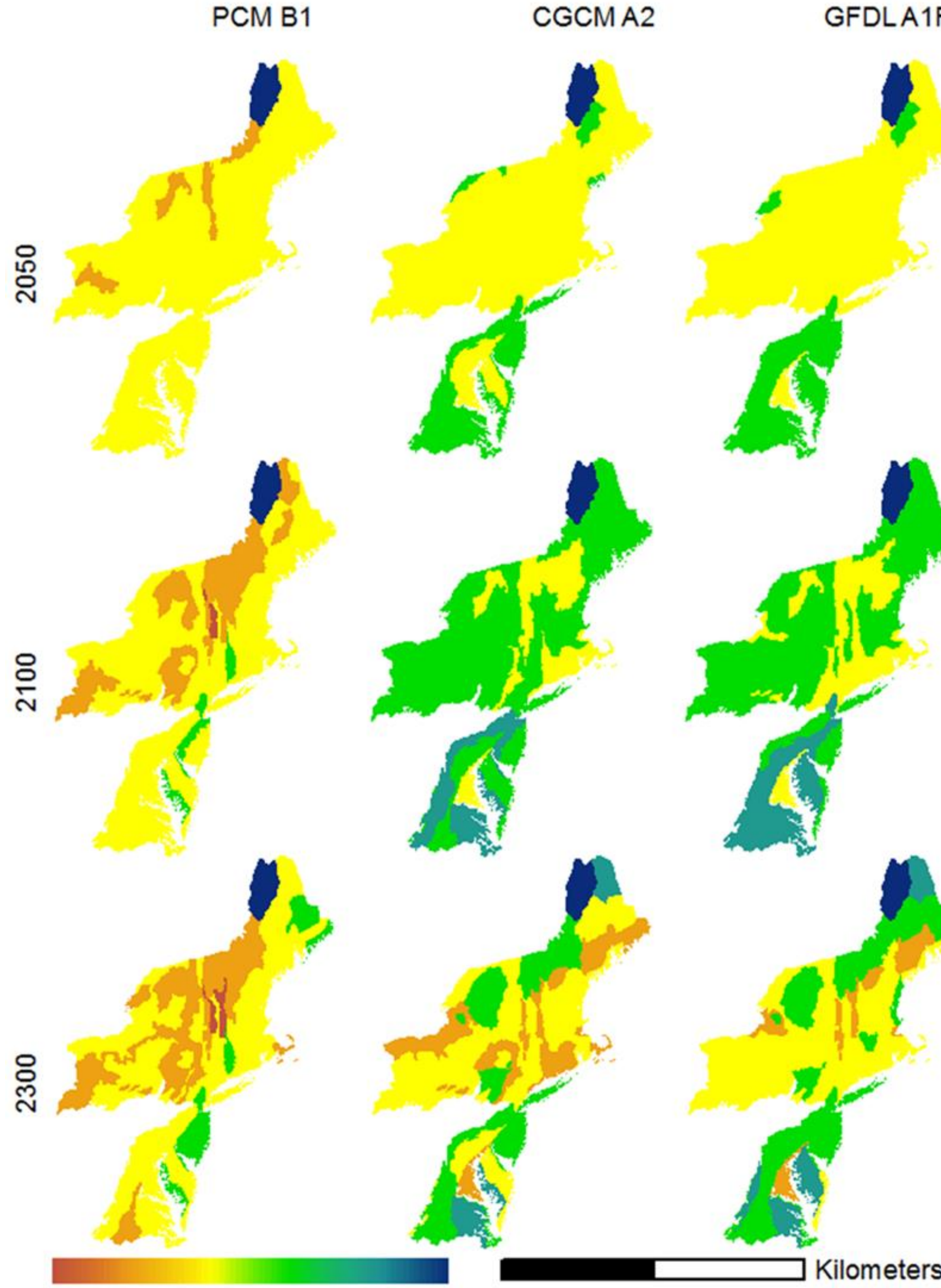

Fig. 1.4. Predicted species occurrences (%) for 24 tree species under current climate, PCM B1, CGCM A2, and GFDL A1FI modeling scenarios at 2050, 2100, and 2300 in the northeastern United States.

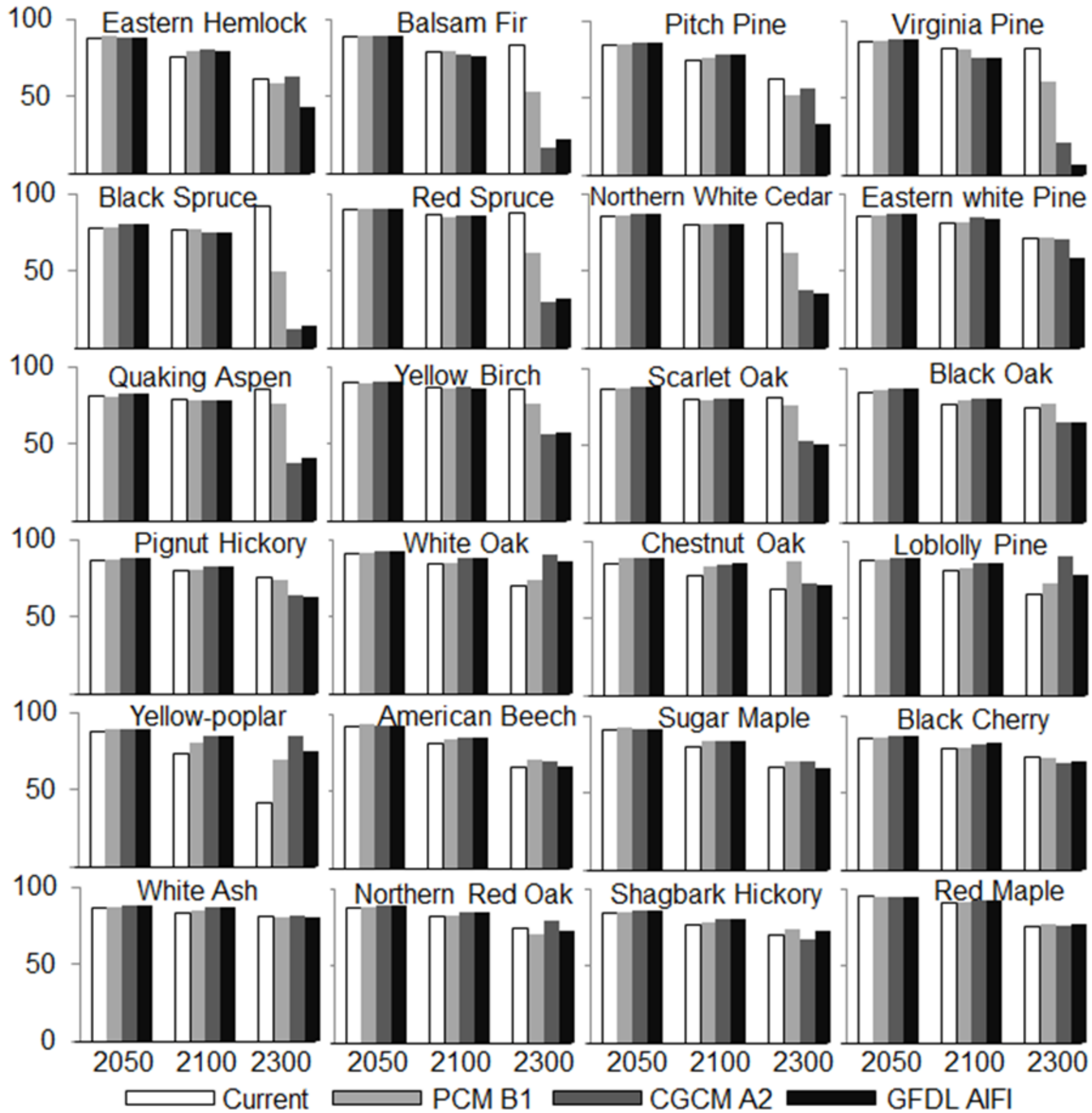

Fig. 1.5 Predicted extinction (in red), colonization (in green), and persistence (in blue) rates for 24 tree species under PCM B1, CGCM A2, and GFDL A1FI modeling scenarios at 2300 in the northeastern United States.

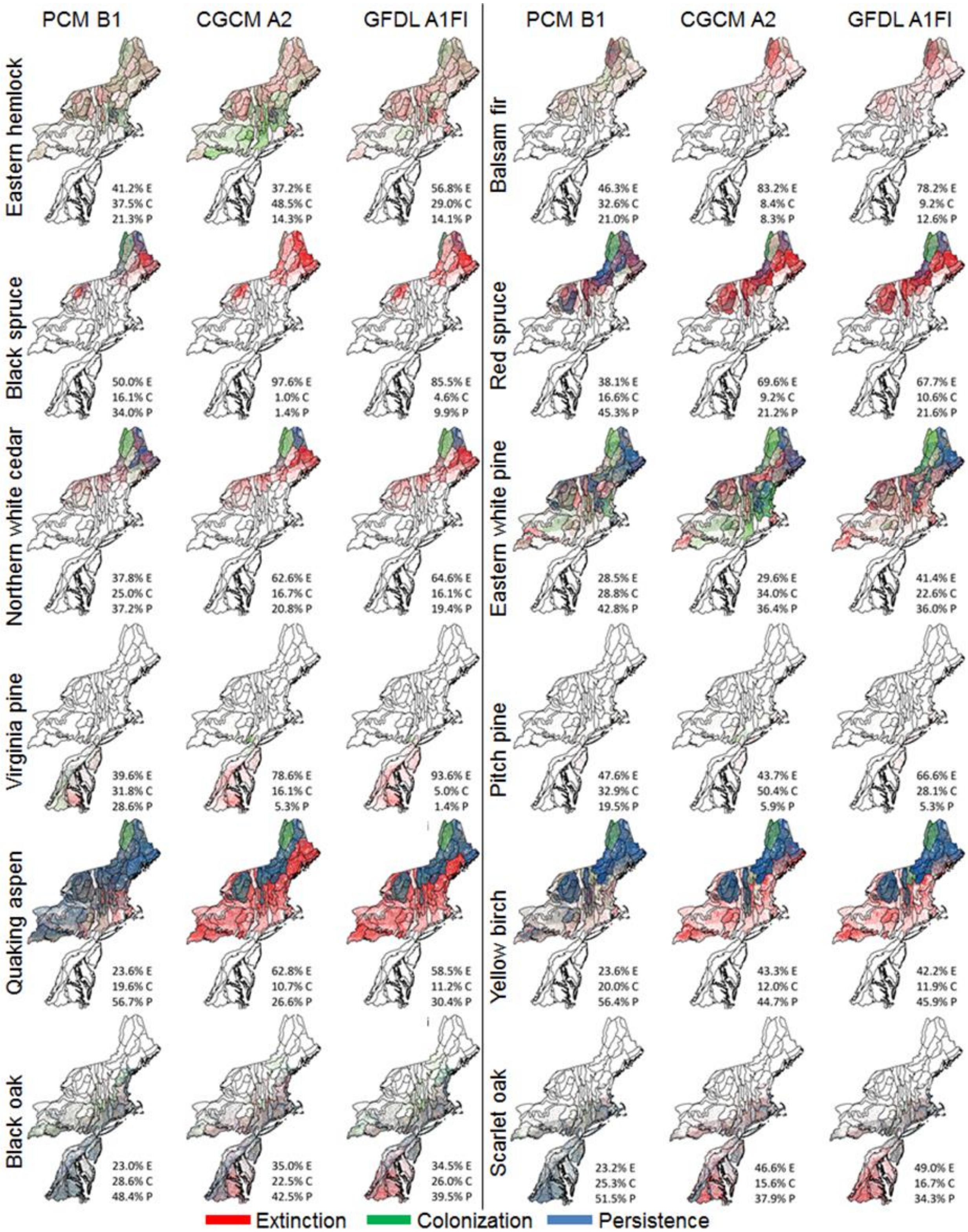

Fig. 1.5 continued.

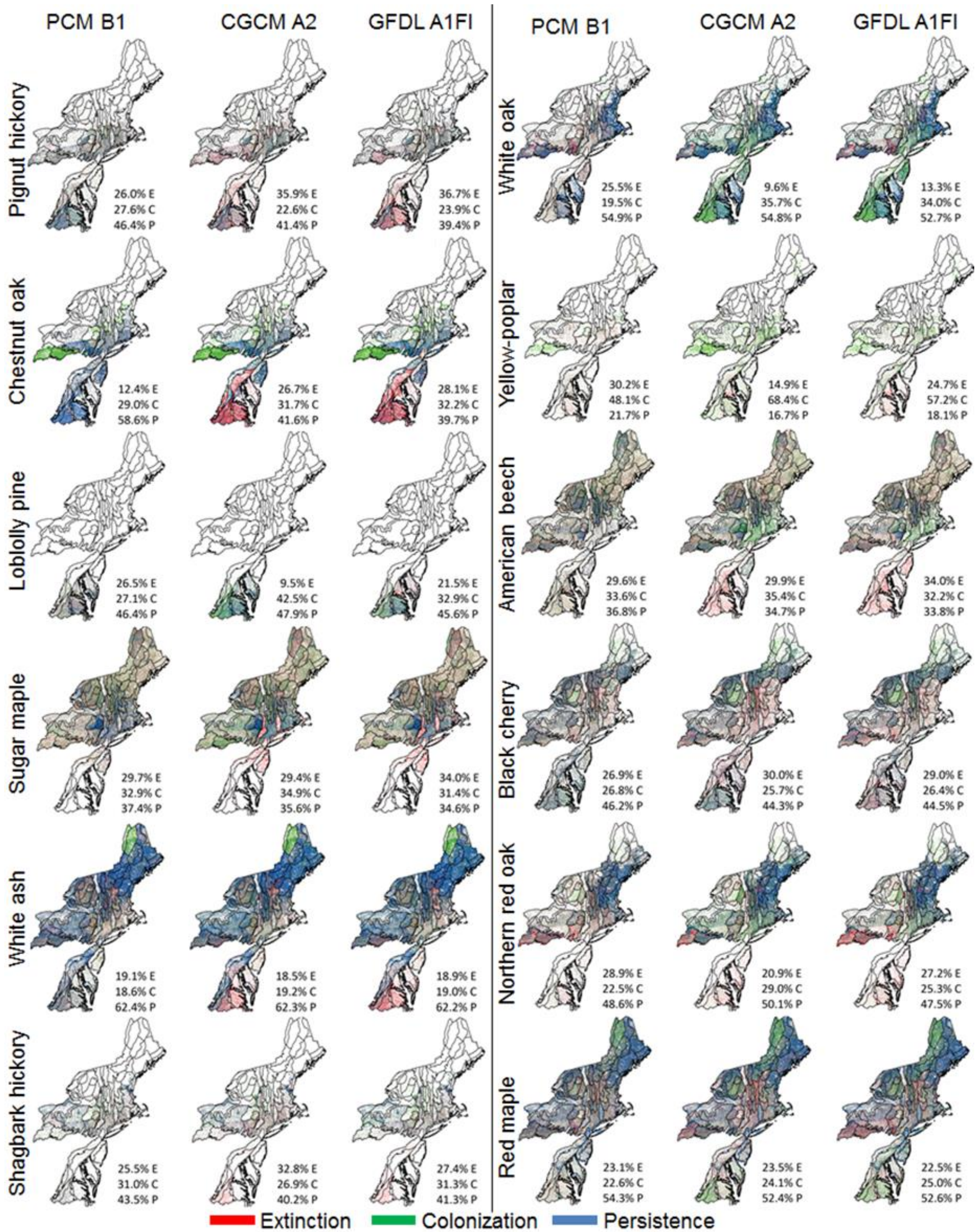

Table 2.1. Attributes of each region. Climate and soil parameters were generated by aggregating 10 x 10 km data within each region. CH=Central Hardwoods, CA=Central Appalachians, MA=MidAtlantic, NE=New England.

Attribute	**CH**	**CA**	**MA**	**NE**
Area, km^2 X 1000	170.10	116.00	245.20	212.30
Mean center, latitude	38.1	39.4	41.1	44.2
Mean center, longitude	-90.0	-81.1	-76.8	-71.5
Number of species represented	20	15	24	24
Mean Annual Temperature, C	13.0	10.8	9.6	6.4
Mean Annual Precipitation, mm	1139	1099	1106	1172
PCM Mean Annual Temperature, C	14.2	11.7	10.7	7.6
PCM Mean Annual Precipitation, mm	1184	1144	1158	1170
GFDL Mean Annual Temperature, C	17.5	15.0	13.7	10.3
GFDL Mean Annual Precipitation, mm	1037	1102	1161	1206
Mean Maximum elevation, m	288	570	439	482
Clay, percent	33.9	27.9	19.1	10.8
Organic Matter, percent	0.8	1.8	2.5	8.8
Available Water Supply, mm	21.3	16.2	15.5	16.7
pH	5.81	5.48	5.45	5.41

Table 2.2. Comparison of change classes for 30 species for TreeAtlas, LINKAGES, and Landis100 and Landis300 for PCM and GFDL climate change scenarios, for the New England (NE, N=24), MidAtlantic (MA, N=24), Central Appalachians (CA, N=15), and Central Hardwoods (CH, N=20) regions. LgDec=large decrease (future:current ratio <0.5), SmDec=small decrease (future:current ratio >0.5 & <0.2), NoChng=no change (future:current ratio >0.2 & <1.2), SmInc=small increase (future:current ratio >1.2 & <2.0), LgInc=large increase (future:current ratio >2.0), NewHab=new habitat.

		TreeAtlas	Linkages	Landis100	Landis300	TreeAtlas	Linkages	Landis100	Landis300
Common Name	**Genus**	**PCM Change**				**GFDL Change**			
Central Appalachians									
Red Spruce	*Picea*	NoChng	SmDec	LgDec	LgDec	LgDec	LgDec	LgDec	LgDec
American Beech	*Fagus*	NoChng	SmDec	NoChng	SmInc	LgDec	LgDec	SmDec	LgDec
Eastern White Pine	*Pinus*	NoChng	NoChng	NoChng	LgDec	LgDec	LgDec	SmDec	LgDec
Sugar Maple	*Acer*	NoChng	NoChng	NoChng	SmInc	LgDec	LgDec	SmDec	LgDec
White Ash	*Fraxinus*	NoChng	SmDec	No Change	LgDec	LgDec	SmDec	NoChng	LgDec
Black Cherry	*Prunus*	SmDec	SmDec	SmDec	LgDec	LgDec	NoChng	SmDec	LgDec
Red Maple	*Acer*	NoChng	NoChng	SmInc	SmDec	LgDec	NoChng	SmInc	NoChng
Tulip Poplar	*Lireodendron*	NoChng	SmDec	SmInc	SmInc	LgDec	SmInc	SmInc	SmInc
Eastern Hemlok	*Tsuga*	NoChng	NoChng	SmDec	LgDec	SmDec	LgDec	SmDec	LgDec
Northern Red Oak	*Quercus*	NoChng	SmDec	NoChng	SmInc	SmDec	LgDec	NoChng	LgInc
Chestnut Oak	*Quercus*	NoChng	SmDec	NoChng	LgDec	SmDec	SmDec	SmDec	LgDec
Scarlet Oak	*Quercus*	NoChng	SmDec	LgDec	LgDec	SmDec	NoChng	LgDec	LgDec
White Oak	*Quercus*	NoChng	SmDec	SmInc	LgInc	SmInc	NoChng	SmInc	LgInc
Black Oak	*Quercus*	NoChng	SmDec	LgDec	NoChng	LgInc	SmDec	LgDec	SmDec
Loblolly Pine	*Pinus*	NoChng	NoChng	SmInc	LgInc	LgInc	LgInc	LgInc	LgInc
Central Hardwoods									
Scarlet Oak	*Quercus*	SmDec	NoChng	NoChng	NoChng	LgDec	LgDec	NoChng	LgDec
Shagbark Hickory	*Carya*	SmDec	NoChng	SmInc	LgInc	LgDec	LgDec	SmInc	LgDec
American Beech	*Fagus*	NoChng	LgDec	SmDec	NoChng	LgDec	LgDec	SmDec	SmDec
Sugar Maple	*Acer*	SmDec	SmDec	NoChng	SmInc	LgDec	LgDec	NoChng	SmDec
White Ash	*Fraxinus*	SmDec	NoChng	SmInc	LgInc	LgDec	LgDec	NoChng	SmDec
White Oak	*Quercus*	SmDec	SmDec	NoChng	SmInc	LgDec	NoChng	NoChng	NoChng
Northern Red Oak	*Quercus*	NoChng	NoChng	NoChng	SmDec	SmDec	LgDec	NoChng	LgDec
Black Oak	*Quercus*	NoChng	NoChng	NoChng	SmInc	SmDec	LgDec	NoChng	LgDec
Black Cherry	*Prunus*	NoChng	NoChng	SmInc	NoChng	SmDec	SmDec	SmInc	NoChng
Tulip Poplar	*Lireodendron*	SmInc	NoChng	SmInc	LgInc	SmDec	SmInc	SmInc	LgInc
Chestnut Oak	*Quercus*	SmInc	NoChng	NoChng	SmInc	NoChng	LgDec	NoChng	LgDec
Pignut Hickory	*Carya*	SmDec	NoChng	NoChng	NoChng	NoChng	NoChng	NoChng	LgDec
Eastern Redcedar	*Juniperus*	NoChng	NoChng	SmDec	SmDec	NoChng	SmInc	SmDec	SmDec
Mockernut Hickory	*Carya*	NoChng	NoChng	SmInc	SmInc	NoChng	SmInc	SmInc	LgInc
Red Maple	*Acer*	NoChng	NoChng	LgInc	LgInc	SmInc	NoChng	LgInc	LgInc
Sweetgum	*Liquidambar*	LgInc	NoChng	NoChng	SmDec	SmInc	SmInc	NoChng	NoChng
Post Oak	*Quercus*	SmInc	NoChng	NoChng	LgDec	LgInc	SmInc	NoChng	SmDec
Southern Red Oak	*Quercus*	LgInc	SmDec	SmInc	LgInc	LgInc	SmInc	SmInc	LgInc
Shortleaf Pine	*Pinus*	LgInc	SmInc	SmDec	LgDec	LgInc	LgInc	SmDec	LgDec
Loblolly Pine	*Pinus*	LgInc	SmInc	LgDec	LgDec	LgInc	LgInc	LgDec	SmDec

		TreeAtlas	Linkages	Landis100	Landis300	TreeAtlas	Linkages	Landis100	Landis300
Common Name	Genus	PCM Change				GFDL Change			
Mid-Atlantic									
Black Spruce	*Picea*	LgDec	LgDec	LgDec	LgDec	LgDec	LgDec	LgDec	LgDec
Northern White Cedar	*Thuja*	LgDec	LgDec	LgDec	LgDec	LgDec	LgDec	LgDec	LgDec
Balsam Fir	*Abies*	LgDec	LgDec	SmDec	LgDec	LgDec	LgDec	SmDec	LgDec
Red Spruce	*Picea*	LgDec	LgDec	SmDec	LgDec	LgDec	LgDec	SmDec	LgDec
Eastern Hemlok	*Tsuga*	SmDec	NoChng	SmDec	LgDec	LgDec	LgDec	SmDec	LgDec
Eastern White Pine	*Pinus*	SmDec	NoChng	SmDec	LgDec	LgDec	LgDec	SmDec	LgDec
Yellow Birch	*Betula*	NoChng	NoChng	SmInc	NoChng	LgDec	LgDec	SmInc	LgDec
Quaking Aspen	*Populus*	SmDec	NoChng	LgInc	LgInc	LgDec	LgDec	SmInc	LgDec
Black Cherry	*Prunus*	NoChng	SmInc	SmDec	SmDec	LgDec	LgDec	SmDec	SmDec
American Beech	*Fagus*	SmDec	NoChng	SmInc	LgInc	LgDec	LgDec	SmInc	SmInc
Red Maple	*Acer*	NoChng	NoChng	NoChng	SmDec	LgDec	SmDec	NoChng	SmDec
Sugar Maple	*Acer*	NoChng	NoChng	NoChng	SmInc	SmDec	LgDec	NoChng	NoChng
White Ash	*Fraxinus*	NoChng	NoChng	SmInc	SmInc	SmDec	SmDec	SmInc	SmInc
Tulip Poplar	*Lireodendron*	SmInc	SmInc	SmInc	NoChng	SmDec	NoChng	SmInc	SmInc
Pitch Pine	*Pinus*	NoChng	NoChng	SmDec	LgDec	NoChng	LgDec	LgDec	LgDec
Virginia Pine	*Pinus*	NoChng	SmInc	NoChng	LgDec	NoChng	SmDec	NoChng	LgDec
Northern Red Oak	*Quercus*	NoChng	NoChng	SmDec	LgDec	NoChng	SmDec	SmDec	NoChng
Chestnut Oak	*Quercus*	NoChng	SmInc	NoChng	LgInc	NoChng	NoChng	SmInc	LgInc
Pignut Hickory	*Carya*	NoChng	SmInc	SmInc	LgInc	SmInc	LgDec	SmInc	SmInc
Scarlet Oak	*Quercus*	SmInc	SmInc	NoChng	LgInc	SmInc	SmDec	NoChng	SmDec
White Oak	*Quercus*	NoChng	NoChng	SmInc	LgInc	SmInc	NoChng	SmInc	LgInc
Shagbark Hickory	*Carya*	SmInc	SmInc	LgInc	LgInc	LgInc	LgDec	LgInc	LgInc
Black Oak	*Quercus*	NoChng	SmInc	SmDec	SmInc	LgInc	SmDec	SmDec	SmInc
Loblolly Pine	*Pinus*	SmInc	LgInc	LgDec	LgDec	LgInc	SmInc	LgDec	LgDec
New England									
Balsam Fir	*Abies*	SmDec	LgDec	SmDec	LgDec	LgDec	LgDec	LgDec	LgDec
Black Spruce	*Picea*	LgDec	LgDec	SmDec	LgDec	LgDec	LgDec	SmDec	LgDec
Red Spruce	*Picea*	SmDec	LgDec	NoChng	LgDec	LgDec	LgDec	NoChng	LgDec
Northern White Cedar	*Thuja*	SmDec	LgDec	NoChng	LgDec	LgDec	LgDec	NoChng	LgDec
Yellow Birch	*Betula*	NoChng	NoChng	SmInc	LgInc	LgDec	LgDec	SmInc	SmInc
Quaking Aspen	*Populus*	NoChng	NoChng	LgInc	LgInc	LgDec	LgDec	LgInc	LgInc
Eastern Hemlock	*Tsuga*	NoChng	NoChng	SmDec	LgDec	SmDec	NoChng	SmDec	LgDec
Red Maple	*Acer*	NoChng	NoChng	SmDec	LgDec	SmDec	NoChng	SmDec	LgDec
Sugar Maple	*Acer*	NoChng	NoChng	NoChng	SmInc	SmDec	NoChng	NoChng	NoChng
Black Cherry	*Prunus*	NoChng	NoChng	NoChng	NoChng	SmDec	NoChng	NoChng	SmInc
American Beech	*Fagus*	NoChng	SmDec	SmInc	LgInc	SmDec	NoChng	SmInc	SmInc
Eastern White Pine	*Pinus*	NoChng	NoChng	NoChng	LgDec	SmDec	SmInc	NoChng	LgDec
White Ash	*Fraxinus*	SmInc	NoChng	SmInc	LgInc	NoChng	NoChng	SmInc	LgInc
Northern Red Oak	*Quercus*	SmInc	NoChng	NoChng	SmInc	SmInc	NoChng	NoChng	NoChng
Pitch Pine	*Pinus*	NoChng	NoChng	LgDec	LgDec	SmInc	SmInc	LgDec	LgDec
Scarlet Oak	*Quercus*	SmInc	SmInc	SmInc	LgInc	LgInc	SmInc	SmInc	NoChng
Pignut Hickory	*Carya*	SmInc	SmInc	SmInc	LgInc	LgInc	SmInc	SmInc	SmInc
White Oak	*Quercus*	SmInc	NoChng	LgInc	LgInc	LgInc	SmInc	LgInc	LgInc
Tulip Poplar	*Lireodendron*	LgInc	SmInc	SmDec	NoChng	LgInc	LgInc	SmDec	LgDec
Black Oak	*Quercus*	SmInc	SmInc	NoChng	SmInc	LgInc	LgInc	NoChng	NoChng
Chestnut Oak	*Quercus*	SmInc	LgInc	LgInc	LgInc	LgInc	LgInc	LgInc	LgInc
Shagbark Hickory	*Carya*	SmInc	SmInc	LgInc	LgInc	LgInc	LgInc	LgInc	LgInc
Loblolly Pine	*Pinus*	NewHab	LgInc	NoChng	NoChng	NewHab	LgInc	NoChng	NoChng
Virginia Pine	*Pinus*	NewHab	LgInc	LgDec	LgDec	NewHab	LgInc	LgDec	LgInc

Table 2.3. Mean class agreement scores across all species by region and model pairs. Agreement code was 4 points if both change classes were identical, 3 points if one class apart (e.g., No Change and Small Increase or Small Decrease), 2 points if two classes apart but still trending in same direction (e.g, No Change and Large Increase or Large Decrease); 1 point if Small Decrease & Small Increase (opposite trend); and 0 points if opposite trend and one or both are Large Decrease or Large Increase.

Table 3. Class agreement scores by model pair.												
	TreeAtlas-Linkages		TreeAtlas-Landis100		TreeAtlas-Landis300		Linkages-Landis100		Linkages-Landis300		Landis100-Landis300	
	PCM	GFDL	PCM	GFDL	PCM	GFDL	PCM	GFDL	PCM	GFDL	PCM	GFDL
Overall	3.40	3.16	2.46	2.63	2.48	2.78	2.97	2.41	2.92	2.60	3.07	3.11
NewEngland	3.59	3.45	2.68	2.45	2.82	2.55	3.09	2.50	2.86	2.68	3.14	3.41
MidAtlantic	3.46	3.00	3.04	2.33	2.58	2.83	2.92	2.33	3.04	2.33	3.08	3.08
CentApps	3.40	2.87	2.53	2.87	2.27	3.20	3.20	2.60	2.93	3.13	2.80	3.13
CentHard	3.15	3.30	2.05	2.35	2.20	2.70	2.55	2.20	2.95	2.25	3.25	2.80

Table 2.4. Mean class agreement scores across by species across all regions and for two groupings of models and different climate scenarios. Agreement code was 4 points if both change classes were identical, 3 points if one class apart (e.g., No Change and Small Increase or Small Decrease), 2 points if two classes apart but still trending in same direction (e.g, No Change and Large Increase or Large Decrease); 1 point if Small Decrease & Small Increase (opposite trend); and 0 points if opposite trend and one or both are Large Decrease or Large Increase.

Common Name	Genus	Number	All combinations PCM&GFDL	TreeAtlas-Linkages-Landis300 PCM&GFDL	PCM	GFDL
Black Spruce	*Picea*	2	3.75	4.00	4.00	4.00
Balsam Fir	*Abies*	2	3.58	3.83	3.67	4.00
Northern White Cedar	*Thuja*	2	3.50	3.83	3.67	4.00
Red Spruce	*Picea*	3	3.28	3.67	3.33	4.00
Sugar Maple	*Acer*	4	3.21	3.17	3.00	3.33
Mockernut Hickory	*Carya*	1	3.17	3.00	3.33	2.67
Chestnut Oak	*Quercus*	4	3.17	3.04	2.92	3.17
Black Cherry	*Prunus*	4	3.15	3.21	3.50	2.92
Pignut Hickory	*Carya*	3	3.08	2.78	3.11	2.44
Eastern Hemlok	*Tsuga*	3	3.06	2.94	2.56	3.33
Scarlet Oak	*Quercus*	4	3.00	3.00	3.17	2.83
Eastern White Pine	*Pinus*	3	2.97	2.83	2.56	3.11
Northern Red Oak	*Quercus*	4	2.97	2.83	2.92	2.75
Eastern Redcedar	*Juniperus*	1	2.92	2.83	3.33	2.33
Red Maple	*Acer*	4	2.88	2.92	3.00	2.83
White Oak	*Quercus*	4	2.88	2.63	2.42	2.83
Sweetgum	*Liquidambar*	1	2.83	2.50	1.67	3.33
Shagbark Hickory	*Carya*	3	2.78	2.94	2.78	3.11
White Ash	*Fraxinus*	4	2.71	2.71	2.58	2.83
Black Oak	*Quercus*	4	2.63	2.83	3.50	2.17
Southern Red Oak	*Quercus*	1	2.58	2.33	1.33	3.33
Virginia Pine	*Pinus*	1	2.56	2.76	3.00	2.53
American Beech	*Fagus*	4	2.52	2.38	2.00	2.75
Yellow Birch	*Betula*	2	2.42	3.00	3.33	2.67
Pitch Pine	*Pinus*	2	2.42	2.33	2.67	2.00
Tulip Poplar	*Lireodendron*	4	2.40	2.17	2.75	1.58
Post Oak	*Quercus*	1	2.17	1.50	1.67	1.33
Loblolly Pine	*Pinus*	3	1.92	1.83	1.56	2.11
Quaking Aspen	*Populus*	2	1.92	2.33	2.00	2.67
Shortleaf Pine	*Pinus*	1	1.17	1.17	1.00	1.33

Table 2.5. Spearman rank correlations for all species by study region and model scenario. Scenarios defined by the following abbreviations: la=Landis, li=Linkages, ta=Tree Atlas, gf=GFDL GCM, pcm=PCM GCM, 100=100 years, 300=300years. Significance of correlations based on Holm's adjusted P-values: bold < 0.0001; bold italics < 0.01; italics < 0.05.

All regions and species									
N=83	la.gf100	la.gf300	la.pcm100	la.pcm300	li.gf	li.pcm	Mlat.dif	ta.gf	ta.pcm
la.gf100	1.00								
la.gf300	**0.70**	1.00							
la.pcm100	**0.99**	**0.67**	1.00						
la.pcm300	**0.84**	**0.75**	**0.84**	1.00					
li.gf	0.24	**0.49**	0.19	0.21	1.00				
li.pcm	0.22	*0.34*	0.22	0.26	**0.54**	1.00			
Mlat.dif	-0.24	**-0.44**	-0.21	-0.28	**-0.84**	**-0.66**	1.00		
ta.gf	0.23	**0.48**	0.20	0.31	**0.77**	**0.65**	**-0.82**	1.00	
ta.pcm	0.25	**0.51**	0.22	*0.34*	**0.76**	**0.60**	**-0.82**	**0.87**	1.00
New England (N=24	la.gf100	la.gf300	la.pcm100	la.pcm300	li.gf	li.pcm	ta.gf	ta.pcm	
la.gf100	1.00								
la.gf300	*0.72*	1.00							
la.pcm100	**0.99**	***0.74***	1.00						
la.pcm300	**0.93**	*0.69*	**0.93**	1.00					
li.gf	0.17	0.27	0.15	0.19	1.00				
li.pcm	0.16	0.30	0.17	0.25	**0.94**	1.00			
ta.gf	0.22	0.35	0.22	0.25	**0.96**	**0.91**	1.00		
ta.pcm	0.21	0.35	0.22	0.27	**0.94**	**0.91**	**0.99**	1.00	
MidAtlantic (N=24	la.gf100	la.gf300	la.pcm100	la.pcm300	li.gf	li.pcm	ta.gf	ta.pcm	
la.gf100	1.00								
la.gf300	*0.71*	1.00							
la.pcm100	**0.99**	*0.66*	1.00						
la.pcm300	**0.89**	**0.80**	0.88	1.00					
li.gf	0.21	*0.67*	0.18	0.36	1.00				
li.pcm	0.25	0.55	0.26	0.41	***0.75***	1.00			
ta.gf	0.23	*0.59*	0.21	0.39	**0.78**	***0.76***	1.00		
ta.pcm	0.38	*0.70*	0.38	0.52	**0.88**	**0.81**	**0.88**	1.00	
CentApps (N=15)	la.gf100	la.gf300	la.pcm100	la.pcm300	li.gf	li.pcm	ta.gf	ta.pcm	
la.gf100	1.00								
la.gf300	0.70	1.00							
la.pcm100	**0.99**	0.62	1.00						
la.pcm300	0.63	**0.92**	0.54	1.00					
li.gf	0.52	0.58	0.54	0.38	1.00				
li.pcm	0.35	-0.02	0.40	-0.01	0.15	1.00			
ta.gf	0.12	0.40	0.10	0.40	0.23	0.11	1.00		
ta.pcm	0.37	*0.62*	0.33	*0.74*	0.40	0.02	0.43	1.00	
CentHard (N=20)	la.gf100	la.gf300	la.pcm100	la.pcm300	li.gf	li.pcm	ta.gf	ta.pcm	
la.gf100iv.fc	1.00								
la.gf300iv.fc	0.62	1.00							
la.pcm100iv.fc	**0.98**	0.55	1.00						
la.pcm300iv.fc	*0.73*	0.45	*0.78*	1.00					
li.gf.fc	-0.09	0.40	-0.17	-0.33	1.00				
li.pcm.fc	-0.01	0.19	-0.06	-0.26	*0.70*	1.00			
t.gf.fc	-0.02	0.28	-0.09	-0.25	*0.77*	0.51	1.00		
t.pcm.fc	-0.12	0.36	-0.15	-0.19	0.64	0.35	***0.80***	1.00	

Table 2.6. Average Future:Current ratios across all models and regions, by climate change scenario.

Common Name	average F:C ratio PCM	range	average F:C ratio GFDL	range	average F:C ratio both
Black Spruce	0.27	0.08-0.45	0.13	0.01-0.47	0.20
Balsam Fir	0.32	0.04-0.57	0.17	0.01-0.5	0.25
Northern White Cedar	0.35	0.12-0.58	0.25	0.05-0.62	0.30
Red Spruce	0.52	0.08-0.88	0.36	0.04-0.8	0.44
Eastern Hemlock	0.65	0.09-1.02	0.41	0.05-0.76	0.53
Eastern White Pine	0.74	0.29-1.07	0.61	0.24-1.13	0.68
Pitch Pine	0.67	0.02-1.17	0.87	0.01-1.76	0.77
Sugar Maple	1.03	0.79-1.47	0.59	0.28-0.99	0.81
Black Cherry	0.90	0.67-1.21	0.84	0.53-1.28	0.87
Eastern Redcedar	0.81	0.56-1.13	1.02	0.64-1.95	0.91
American Beech	1.17	0.66-1.93	0.74	0.21-1.28	0.96
Yellow Birch	1.24	0.83-2.11	0.69	0.17-1.63	0.96
Northern Red Oak	0.98	0.69-1.34	1.08	0.51-2.25	1.03
Post Oak	0.86	0.35-1.22	1.38	0.6-2.25	1.12
Scarlet Oak	1.27	0.81-2.06	0.97	0.45-1.81	1.12
Black Oak	1.12	0.76-1.47	1.14	0.48-2.32	1.13
Pignut Hickory	1.28	0.84-1.92	1.23	0.61-1.99	1.25
White Ash	1.24	0.68-1.99	1.31	0.4-3.04	1.28
Sweetgum	1.23	0.57-2.47	1.33	0.89-1.78	1.28
Shortleaf Pine	1.00	0.04-2.16	1.69	0.05-3.41	1.35
Mockernut Hickory	1.30	0.88-1.92	1.56	1.11-2.52	1.43
Red Maple	1.22	0.57-2.11	2.16	0.51-5.88	1.69
White Oak	1.65	0.9-2.92	1.78	1.03-2.92	1.71
Tulip Poplar	1.46	0.87-2.32	2.28	0.43-5.53	1.87
Shagbark Hickory	2.22	1.23-4.31	2.36	0.95-4.47	2.29
Quaking Aspen	3.34	0.69-9.4	1.32	0.12-3.81	2.33
Chestnut Oak	2.26	1.05-5.04	2.57	0.87-5.31	2.41
Southern Red Oak	3.28	0.79-6.2	3.45	1.33-6.92	3.36
Loblolly Pine	2.48	0.53-6.91	6.26	0.77-15.44	4.37
Virginia Pine	1.53	0.2-3.24	7.66	0.07-17.23	4.59

Fig. 2.1 Locations of the study regions used in model comparison and synthesis in the Eastern United States.

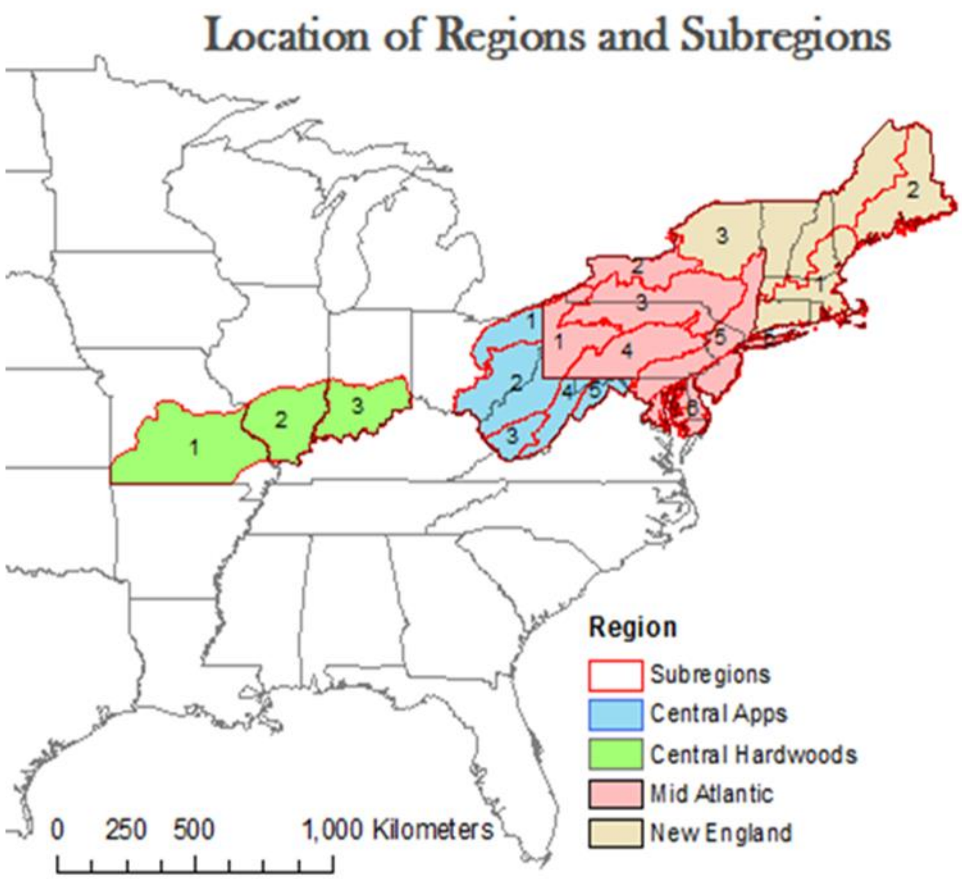

Fig. 2.2 Spearman Rank correlations of future:current ratios among models and climate scenarios for all four regions together. Scenarios defined by the following abbreviations: la=Landis, li=Linkages, ta=Tree Atlas, gf=GFDL GCM, pcm=PCM GCM, 100=100 years, 300=300years.